

A Hard X-Ray Telescope Science Enhancement Package for the Constellation X-Ray Mission

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1. ABSTRACT

Details of a hard-x-ray science enhancement package for the Constellation-X mission are presented. A scientific case is made for the inclusion of such an instrument on the planned mission and a detailed design is presented that will satisfy science requirements yet fall within the ground rules for enhancement packages: a cost of less than \$100M and a mass of no more than 100 kg.

2. INTRODUCTION

The instrument described here was proposed in response to the Constellation-X solicitation of "white papers" containing concepts for the Science Enhancement Package (SEP) that will augment the capability of the mission¹. The SEP is required to be compatible with a redesigned spacecraft and launch vehicle that are smaller than before. The premise is that the effective area and bandwidth of the soft-x-ray telescope (SXT) will remain essentially the same as in the original design. Any additions should add no more than 100 kg to the mass of the payload and no more than \$100 M to the cost.

The motive behind this proposal is the concern that the bandwidth of the SXT is not sufficiently broad to accomplish one of the most important scientific objectives of the Constellation X-Ray Mission: obtaining unambiguous measurements of the profile of a K α fluorescence line of iron that has been redshifted into a broadly extended feature by strong gravity forces in the vicinity of an accreting black hole. The proposed instrument is a hard-x-ray telescope (HXT) that extends the bandwidth of Con-X and permits measurements of the magnitude and functional form of the continuum on which the Fe feature sits. The continuum spectrum in the vicinity of the Fe line may be influenced by the "Compton hump" that is present in the X-ray spectrum of a black hole. The SXT will not be able to detect it over an energy range that is sufficiently large to define its functional form because the Compton hump reaches a peak at an energy beyond its high energy cutoff.

3. SCIENTIFIC JUSTIFICATION

Observing and quantifying the gravitational redshift in the vicinity of black holes is a major, if not the most important, scientific objective of Con-X as this will provide new information about the behavior of matter in strong gravitational fields and the laws of general relativity. The nearby ($z = 0.00775$) Seyfert galaxy MCG-6-30-15 contains a prime example of a gravitationally-broadened Fe line. The abundance of iron is 2 to 3 times solar², which makes it a particularly good object from which to draw conclusions about the broad Fe feature. The broad-line effect was discovered by ASCA³ and has been observed since by ASCA again on several occasions, as well as BeppoSAX⁴ and RXTE⁵. Furthermore, there was a long XMM-Newton exposure⁶ and a more recent Suzaku observation⁷. In⁸, several models were considered including the spin of the black hole that could explain the shape of the broad Fe line.

A figure in the Suzaku paper illustrates why it is desirable to have good data at 20 keV and above for interpreting the spectrum. Figure 1 is the energy spectrum of MCG-6-30-15 relative to a function that varies as E^{-2} . The points at energies up to 12 keV are data from the CCD detectors (XIS) and the higher energy points, which extend to about 40 keV were obtained by a combination of a PIN diode and a GSO crystal scintillator.

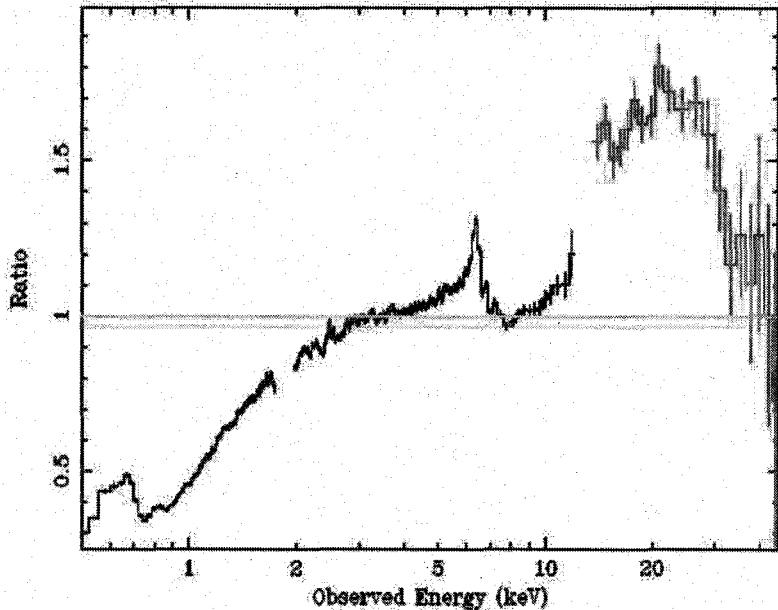


Fig. 1: Energy spectrum relative to the function E^2 of the Seyfert galaxy MCG-6-30-15 as seen by Suzaku. This figure is a reproduction of Fig. 4 of paper⁷.

Between the Compton hump whose effects appear to extend down to the region of the Fe line, the broadened Fe line, and the absorption at low energy, the energy range where the ratio of the observed spectrum to a power law continuum is constant is very small. Consequently there is considerable ambiguity concerning the isolation of the broadened Fe line from the continuum and what its exact shape is.

Figure 2 is reconstructed from the Suzaku data shown in Figure 1. The Suzaku data points (circles) are the ratios with respect to a continuum function that varies as E^{-2} . Two other sets of simulated data points are shown: one is obtained by changing the amplitude of the E^{-2} reference function by 2% (crosses) and the other by changing the power law reference function by 5% to $E^{-2.1}$ (squares). Differences among the three sets of points illustrate the ambiguity of determining the precise shape of the gravitationally-broadened Fe line and how dependent that is upon the knowledge of the continuum. Figure 1 suggests that the influence of the Compton hump persists down to 7 keV and perhaps even lower. Con-X will certainly observe many other objects with the goal of studying the gravitationally-broadened Fe line. These observations may include cases where the Compton hump has even greater influence upon the continuum in the region of the red shifted Fe line.

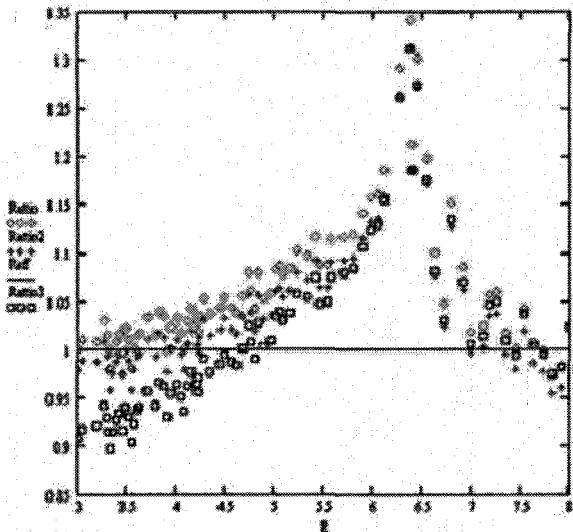


Fig. 2: Suzaku data points that appear in Fig. 2 of paper⁹ are reproduced here without the error bars (red circles). Two other sets of data points are shown, blue crosses and black squares, based upon slightly different underlying continuum spectra (see text).

A recent XMM-Newton publication⁹ contains a figure, which is reproduced below in part (Figure 3), that shows the presence of broadened Fe lines in eight Seyfert galaxies. In each case the data have larger errors than the MGC-6-30-15 data but one can see that the Fe line profile varies considerably from one object to another. This is not surprising given that the black holes at the center of each Seyfert do not all have the same mass and spin. Most cases exhibit significant changes in the continuum with respect to a power law spectrum with a constant spectral index even below 10 keV. In addition a very strong correlation between the intrinsic spectral slope in X-rays and the amount of Compton reflection in Seyfert AGNs has been reported¹⁰.

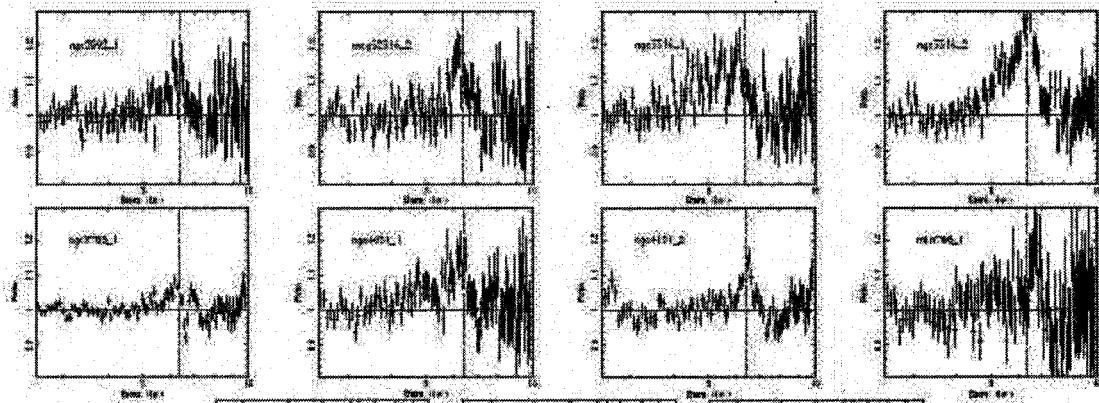


Fig. 3: Spectra of eight Seyfert galaxies relative to a power law reference as observed by XMMNewton (taken from a figure that appears in⁹).

There is no doubt the evidence for a gravitationally-redshifted Fe is supported by observations of ASCA, Suzaku, and XMM-Newton. However, in all cases the error bars are large and one can have doubts that the contribution of the continuum to the spectrum below 6.4 keV has been taken into account accurately. Con-X will no doubt be able to reduce the error bars significantly and measure the energy profile of the redshifted Fe line plus continuum much more

precisely. (Thanks to the high spectral resolution of the detectors Con-X will also be able to detect for the first time absorption edges and absorption lines in the profile.) However, in order to subtract the continuum and isolate the Fe line profile unambiguously it will be necessary to observe the continuum and Compton hump over an energy band that extends beyond the high energy cutoff of the SXT.

Furthermore, we note that Con-X will be a national observatory devoted to X-ray spectroscopy for use by many observers. They will be pursuing a wide variety of science objectives that will be enabled by or can benefit from extending the bandwidth of Con-X. Non-thermal processes, e.g. synchrotron radiation and inverse Compton scattering are factors in radiation from AGN jets and highly magnetized neutron stars. Non-thermal X-rays are usually more prominent at higher energy than the current limit of the SXT. Studies involving non-thermal X-rays will reap large benefits from extending the bandwidth of Con-X. Because background is reduced by orders of magnitude a focusing telescope operating in the 15 to 40 keV band will have orders of magnitude more sensitivity in pointed measurements than all previous instrument.

4. TECHNICAL DESCRIPTION

3.1 Overview

The purpose of the proposed hard X-ray telescope system for a Con-X Science Enhancement Package is to extend the bandwidth beyond the high-energy cutoff of the SXT. The concept is based upon technology developed and tested for the original Con-X HXT that was removed in the recent mission re-design. The difference is the telescope modules are each lighter weight and there are fewer, two as compared to the original twelve. Our HXT concept utilizes multilayer-coated nickel optics coupled with cadmium-zinc-telluride focal plane detectors, optimized to provide a significant increase in collecting area above 15 keV.

The proposed optics are manufactured using a replication process in which thin nickel shells are electroformed on super-polished aluminum masters (mandrels) from which they are later released by differential thermal expansion. The resulting full-shell optics are inherently stable and deliver good angular resolution performance when simply held in locating spiders at their two ends. The electroformed-nickel-replication (ENR) process has been used very successfully on previous missions to fabricate the telescopes for Swift and XMM-Newton.

MSFC has an ENR development program that has produced mirror shells up to a factor of ~four times thinner than the thinnest shells used on XMM. Test shells, 100-microns-thick, and of diameters 15 and 23 cm have been coated with multilayers at SAO and mounted by colleagues at the Brera Observatory, Italy (Figure 4). They were tested in UV light at Brera and with X-rays at the Panter facility in Germany. To date, better than 30 arcsec HPD has been demonstrated and that is mostly limited by the mounting process. A new mounting and alignment system, currently under development at MSFC, promises better performance. Our performance goal is 20 arcsec HPD for mounted shells. Details of the fabrication, coating, and testing appears in various publications^{11,12}, and the alignment system is

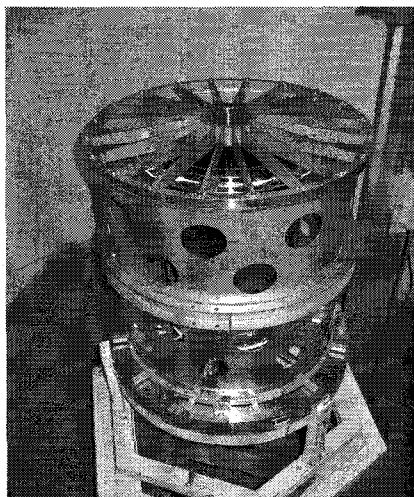


Fig. 4: Two 100-micron-thick test mirror shells installed in structure prior to testing at the Panter facility.

described elsewhere in this volume¹³.

According to the SXT model's predictions it has an effective (system) area of 240 cm² at 15 keV, dropping to just 41 cm² at 20 keV. The function of the hard X-ray telescopes is to extend the energy band past 15 keV. Both iridium and multilayer coatings can be employed to provide significant effective area at high-energy. For example, the 23-cm mirror shell of the telescope shown in Figure 4 was coated with a W/Si multilayer whose period was graded with depth, while the 15-cm mirror was coated with iridium. The coating assignments of the mirrors determine the energy band. Greater use of multilayer coatings favors effective area at the higher energy end of the band at the expense of the effective area at lower energy. Figure 6 shows the effective area of one possible set of (all multilayer) coatings. There is a wide range of possibilities for the Con-X Facility Science Team or other scientific committees to select the best science-driven effective area requirements.

For the focus of the above mirror modules pixellated detector arrays based on the room temperature semiconductor compound Cadmium-Zinc-Telluride (CZT) is proposed. These have high efficiency and good energy resolution in the energy range of interest and are well developed¹⁴. This is the type of detector selected for the original HXT.

3.2 Configuration

A two-module configuration is proposed for the enhancement package that maximizes the required collecting area function within the given SEP weight budget. The modules are located outboard of the SXT optics in either the three or four SXT configurations under consideration, as shown in Figure 5 below for the 4 optic case. The 4-SXT option places the HXT detector close to, but not outside, the edge of the detector bench. Note that in this SXT configuration there is ample room inside the central mirror bench area to accommodate both HXT optics, but some documents show SXT-detector-related hardware in the central detector bench area, which could preclude its use for the HXT detectors.

The two identical mirror modules each consist of 68 nested nickel-alloy shells ranging in diameter from 15 cm to 34 cm. The shells are 60 cm total length and are a monolithic structure containing both 'P' and 'H' segments. Note that up to 10 extra shells can be added per module if the mass contingency allocated is not used.

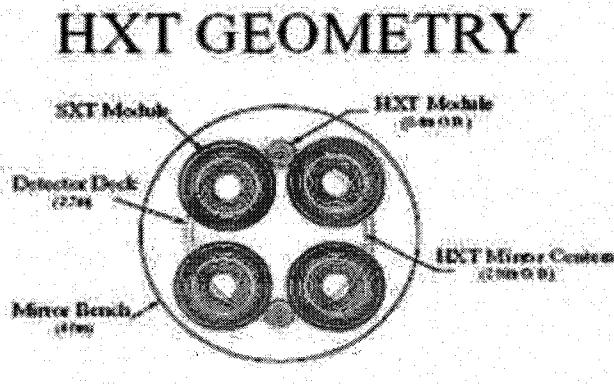


Fig. 5: Location of HXT telescopes, the 2 small (red) circles. SXT mirrors are the 4 larger (blue) circles.

The shells are fabricated from a high-strength nickel alloy and are 100 micron thick out to 25 cm diameter, gradually increasing to 150 microns thick at 34 cm. A composite housing, matched to the thermal expansion coefficient of nickel contains the shells which are held in place by a pair of diamond turned spiders, fabricated in steel. The outer diameter of each mirror module, including thermal insulation, is 40 cm, and the full module length is 66 cm.

The proposed focal plane detectors are based on those developed for the HEFT and NuSTAR programs¹⁵. These are pixellated cadmium-zinc-telluride devices with custom readout chips and have high quantum efficiency and excellent energy resolution (< 1 keV FWHM) over the bandwidth of interest. The pixel size is well matched to our optics: a 500-micron-resolution detector oversamples a 10-m-focal length, 20 arcsec HPD optic by a factor of two, leading to an overall system resolution of 22 arcsec. Total detector power (2 units) is expected to be around 12 W, including detector heaters, but excluding mirror thermal control.

For estimating the overall detector dimensions and weights we have based our concept on the device developed for the NuSTAR SMEX payload¹⁶. The envelope for each detector unit, 15.0 cm diameter including active shields and thermal insulation, is estimated to be just inside the detector bench in the 4 SXT configuration shown in Figure 5.

Mass numbers, see Table 1 below, are derived from the calculated weights of the mirror shells in the configuration described above and the housing mass is scaled from those previously used in the HERO balloon payload. The mass of each detector system is based upon that previously generated for Con-X and the NuSTAR experience.

Table 1: Estimated Total Mass for 2 HXT Telescopes

Item	Mass (kg)
Shells	29.6
Housings + blanket	6.75
Detectors	7.7
Sub-total per telescope	44.1
Central electronics unit	2.7
Contingency (10%)	9.0
Total	99.8

3.3 Performance

Figure 6, below, shows the total system effective area as a function of energy for the proposed two-telescope configuration.

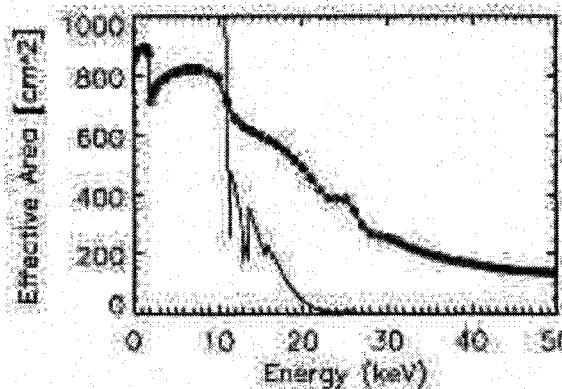


Fig. 6: Effective area (upper curve) of the proposed 2-telescope HXT as a function of energy. The lower curve represents the SXT area in the 4-telescope configuration.

The expected (5s) continuum sensitivity ($dE/E = 50\%$) has been calculated for the HXT configuration with this total effective area. Figure 7 shows this as a function of energy for two integration times, 10^5 sec and 10^6 sec. The background for this calculation was taken from a detailed simulation of an HXT reference configuration in an L2 orbit¹⁷. Note that most of the detector weight in the above table is in the BGO/CsI anticoincidence shields. Lighter shields could be investigated (such as plastic scintillators plus a modest amount of passive shielding); the small focal spot of the 22 arcsec optics helps in this regard as a factor of two increase in background at 20 keV only degrades the 10^5 sec sensitivity by 10%.

Fig. 7: Continuum sensitivity of the proposed 2-telescope HXT configuration. Shown are (5-sigma) curves for 10^5 and 10^6 sec

<http://constellation.gsfc.nasa.gov/>

² Fabian, A. C., Vaughan, S., Nandra, K., Iwasawa, K., Ballantyne, D. R., Lee, J. C., De Rosa, A., Turner, A. Young, A. J., A long hard look at MCG-6-30-15 with XMM-Newton, *MNRAS* **335**, L1, 2002.

³ Tanaka, Y., Nandra, K., Fabian, A. C., Inoue, H., Otani, C., Dotani, T., Hayashida, K., Iwasawa, K., Kii, T., Kunieda, H., Gravitationally Redshifted Emission Implying an Accretion Disk and Massive Black-Hole in the Active Galaxy MCG-6-30-15, *Nature* **375**, 659, 1995.

⁴ Guainazzi, M., Matt, G., Molendi, S., Orr, A., Fiore, F., Grandi, P., Matteuzzi, A., Mineo, T., Perola, G. C., Parmar, A. N., Piro, L., BeppoSAX confirms extreme relativistic effects in the X-ray spectrum of MCG-6-30-15, *A & A* **341**, L27, 1999.

⁵ Vaughan, S. and Edelson, R., Evidence for Rapid Iron Ka Line Flux Variability in MCG-6-30-15 *ApJ* **548**, 694, 2001.

⁶ Wilms J. Reynolds, C. S., Begelman, M. C. Reeves. J., Molendi S., Struber, R., and Kendziorra, E., *XMM-EPIC observation of MCG-6-30-15: direct evidence for the extraction of energy from a spinning black hole?* MNRAS **328**, L27, 2001.

⁷ Miniutti, G., Fabian, A., Anabuki, N., Crummy, J., Fukazawa, Y., Gallo, L., Haba, Y., Hayashida, K., Holt, S., Kunieda, H., and 14 coauthors, *Suzaku Observations of the Hard X-Ray Variability of MCG -6-30-15: the Effects of Strong Gravity around a Kerr Black Hole*, 2006, PASJ (in press). Also astro-ph 0609521.

⁸ Brenneman, L. W., Reynolds, C. S., *Constraining Black Hole Spin via X-Ray Spectroscopy*, Ap.J. **652**, 1028.

⁹ Nandra, K, O'Neil, P. M., George, I. M., Reeves, J. N. and Turner, T. J., *An XMM-Newton survey of broad iron lines in AGN*, Astron. Nachr. **999**, 789, 2006.

¹⁰ Zdziarski, A. A., Lubinski, P., and Smith, D. A., Correlation between Compton reflection and X-ray slope in Seyferts and X-ray binaries, MNRAS **303**, L11, 1999.

¹¹ Ramsey, B., R. Elsner, D. Engelhaupt, M. Gubarev, J. Kolodziejczak, S. O'Dell, C. Speegle and M. Weisskopf, “*The development of hard-x-ray optics at MSFC*,” SPIE **5168**, 129, 2003.

¹² Romaine, S., et. al., “*Development of a prototype nickel optic for the Constellation-X hard x-ray telescope: III (Proceedings Paper)*”, SPIE **5900**, 59, 2005.

¹³ Gubarev M., Arnold, W., Benson, C., Kester, T., Lehner, D., Ramsey, B. and Upton, R., “*Mounting and Alignment of Full-Shell Replicated X-Ray Optics*,” this volume.

¹⁴ Chen, C., Cook, W., Harrison, F., Lin, J., Mao, P. and Schindler, S., “*Characterization of the HEFT CdZnTe pixel detectors*,” SPIE **5198**, 9, 2004.

¹⁵ <http://www.nustar.caltech.edu/>

¹⁶ Fiona Harrison/Caltech: private communication.

¹⁷ Armstrong, T.W., Colborn, B.L. and Ramsey, B.D., “*Initial estimates of radiation backgrounds for the hard-x-ray telescope on the planned Constellation-X Mission*,” SAIC-TN-99015R2, 1999.